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14. ABSTRACT This program of research had as its focus the development and implementation of a synergistic measurement system in which the sensing and processing of ultrasonic signals comprise an autonomous and intelligent measurement system capable of processing a diversity of sensory signals to model, forecast and possibly even control the condition of a material or a structure with respect to its performance. The intended application was to a procedure by which damage in aircraft materials and structures can be tracked and its evolution predicted. Two principal tasks were completed under this contract: (1) Several new airframe structure, wide-area, ultrasonic inspection techniques were explored and the sensory input signals were input into a novel diagnostic system; and (2) A general non-destructive material property and performance prediction system was demonstrated which is capable of processing a wide diversity of inspection and maintenance data. These tasks addressed two recommendations which had been made by a national committee for near- and long-term research related to the nondestructive evaluation and maintenance technology for aircraft.					
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FINAL REPORT

NEW SIGNAL PROCESSING TECHNIQUES TO INTERPRET, TRACK AND PREDICT DAMAGE IN AIRCRAFT MATERIALS AND STRUCTURES

Contract: F49620-98-1-0338

1 MAR 1998 – 1 SEP 2000 (Plus No-cost Extension to 31 MAR 2001)

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Abstract:

This program of research had as its focus the development and implementation of a synergistic measurement system in which the sensing and processing of ultrasonic signals comprise an autonomous and intelligent measurement system capable of processing a diversity of sensory signals to model, forecast and possibly even control the condition of a material or a structure with respect to its performance. The intended application was to a procedure by which damage in aircraft materials and structures can be tracked and its evolution predicted. Two principal tasks were completed under this contract: (1) Several new airframe structure, wide-area, ultrasonic inspection techniques were explored and the sensory input signals were input into a novel diagnostic system; and (2) A general non-destructive material property and performance prediction system was demonstrated which is capable of processing a wide diversity of inspection and maintenance data. These tasks addressed two recommendations which had been made by a national committee for near- and long-term research related to the nondestructive evaluation and maintenance technology for aircraft. The work completed under this contract has addressed a wide variety of ultrasonic inspection problems as well as developed a procedure for forecasting the growth rate of a fatigue crack and even the lifetime of a specimen that is based on previous measured data. As such, this work lays the foundation for solving a number of practical and challenging problems of interest to the Air Force.

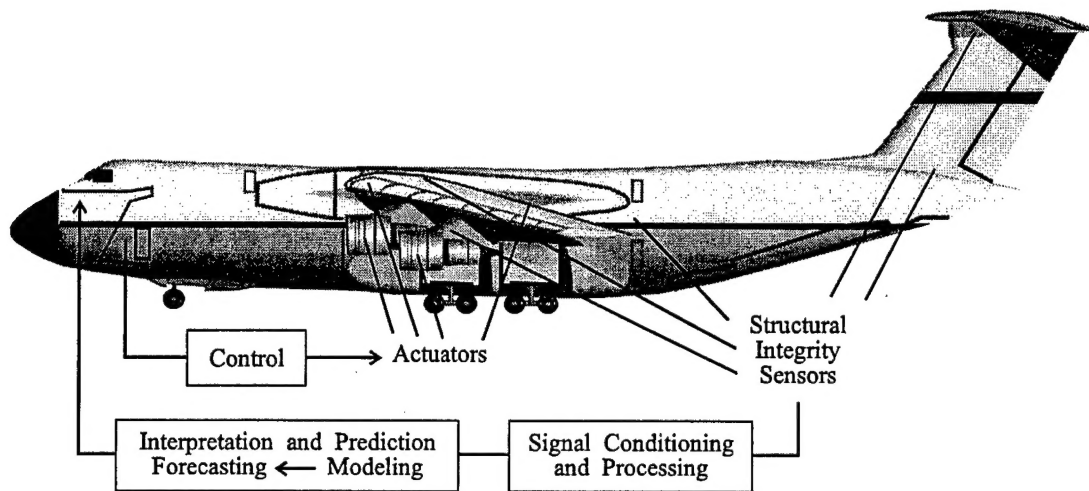


Figure 1: Schematic diagram of a *synergistic diagnostic* system as it might be implemented in an aircraft.

Program Overview:

The focus of this project was the development and implementation of a synergistic measurement system in which the sensing and processing of ultrasonic signals can be used to model, forecast and possibly even control the condition of a material or a structure with respect to its performance. The duration of this project was from March 1, 1998 to September 1, 2000 with a no-cost extension to March 31, 2001.

The key element in the system we proposed was an information processing system which we had developed previously and which was capable of automatic observation, modeling and even controlling a system [1]. The measurement system as it might be employed on-line in an aircraft to detect and track the development structural damage in the aircraft is shown schematically in Fig. 1. The system consists of four essential components. These are: (1) The aircraft part or structure to be monitored; (2) A structure integrity sensor system comprised of one or an array of sensors and a preprocessing unit; (3) An intelligent modeler comprised of a processor and its associated memory of the material or structure degradation process, and (4) An output unit. Such a system is capable of forming an internal representation of the sensed structural integrity data and the corresponding damage condition of the structure. The input to the system is expressed in terms of data vectors which are comprised of two or more partial data $\{X, Y\}$ corresponding to sensory data and an encoded representation of the corresponding damage state of the structure.

In this project the focus was on the sensory network and the processing unit(s). And specifically, a sensory network which consisted of both ultrasonic point-like sensors and direct optical crack length measurements. Much of the project's emphasis was on the signal processing. These included the adaptation and further development of so-called *self-adjusting modelers* which are neural-like, adaptive signal processing procedures; the analysis of long-duration waveforms in the time-frequency domain; and the combination of multiple narrowband burst measurements to form a composite time-resolved broadband impulse that permits time-resolved non-linear ultrasonic measurements.

Accomplishments:

The specific deliverables of this grant and our performance in carrying them out will be reviewed in the following paragraphs.

1. *We were to demonstrate the operation and capabilities of the intelligent structure monitor on a specimen in which a fatigue crack is growing. We were to collect fatigue crack data as a function of various loading parameters in a multi-mode fracture test and track and predict the future evolution of the crack.*
2. *We promised to develop and demonstrate a multi-sensor intelligent structure monitoring system using multi-channel material damage signals. Training and demonstration of the system was to be with data obtained from our own experiments as well as other sources as we could obtain them. The principal goal was to be a demonstration of the predictive characteristics of the monitoring system.*

These deliverables were the key elements in our original proposal and they commanded most of our efforts. The success relied on the development of self-adjusting modelers and the collection of fatigue crack growth data which was obtained using direct optical measurements. Ultrasonic crack sizing approaches were also explored. High-cycle fatigue data supplied by T. Nicholas of the USAF Wright Laboratory was also analyzed. As these topics form the central element of this project, our results will be reviewed in considerable detail.

Self-adjusting Modelers -

Following on our earlier work [1], we further developed *self-adjusting modelers* for modeling the mechanical properties of materials. [2] The modelers are neural-like, adaptive signal processing procedures which are based on non-parametric regression analysis. The statistical treatment of measured data $\{X, Y\}$ is used to construct modelers by which the natural law $Y = f(X)$ describing the mechanical properties of materials, such as the relationship between ultrasonic waveforms and the location of an acoustic source in a complex structure or the lifetime of a fatigue-loaded specimen and the crack driving force can be found. Without any *a priori* presumed or unjustified assumptions, such *self-adjusting modelers* can be used to model a nonlinear correlation or relationship between signals (and/or their sources) and the property or condition of a material undergoing a complex loading. Also, because a modeler automatically reflects the underlying physics in the measurement, it is capable of predicting a material's properties or response.

With work carried out under this contract we demonstrated how previously-measured data such neural-like, adaptive signal processing procedures can be used to predict the "infinite life curve" or *safe stress* of a Ti-6Al-4V aluminum alloy and the crack growth rate of 2024-T3 and 7075-T6 Al-plate specimens undergoing mixed-mode tension and torsion fatigue loading. Details of this approach are contained in the dissertation of Lu. [2]

Applications -

a. Prediction of High-Cycle Fatigue Response

Cracks remain small for much of the life of a material undergoing *high-cycle fatigue* (HCF)

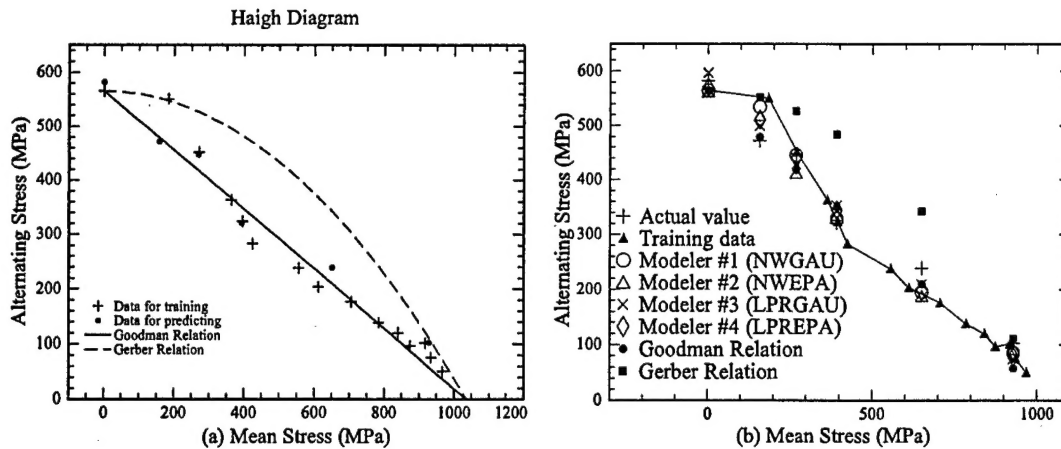


Figure 2: (a) HCF data and empirical relations (b) Results of prediction using four modelers.

and so conventional S-N curves or *Haigh* or *Goodman* diagrams often form the basis of HCF design [3, 4]. In contrast to the S-N diagram in which the effect of the mean stress on the fatigue behavior is not clearly presented, the *Haigh* diagram shows the alternating stress versus the mean stress with lines of constant life drawn through the data points. Among the lines, the curve defining the *infinite-life region* is most important. However, a very large data base is required to generate this curve and the required tests are expensive and time-consuming. The question has been how one can predict stress values on the *Haigh* diagram from a limited number of measurements.

Traditionally *parametric fitting* is used to obtain the best fit of the line defining the *infinite-life region*. The empirical equations include those developed by Goodman and Gerber, among others. [5] While such relations provide some insight to the data, they generally do not give universally satisfactory fitting for all materials and loading conditions. There are other drawbacks related to such parametric fitting. For example, by using a fixed-form equation, the generality of the description of the relations between data is diminished. And such equations generally do not reflect the physics of actual phenomena.

We obtained high cycle fatigue data from T. Nicholas of USAF Wright Laboratory. The data was of Ti-6Al-4V generated by a rapid test procedure at 70 Hz [6] and it is displayed on a *Haigh* diagram as shown in Fig. 2(a) for a constant life of 10^7 cycles at room temperature. Fifteen data points were selected for training and the 6 remaining actual data values which were to be predicted are also shown. Further, the Goodman and Gerber parametric relations are shown for comparison.

Two prediction tests were implemented. The first is a single test in which the last 6 data points of the original 21 points of the data set were selected for prediction with the first 15 points used to train the modelers.¹ Each of the four self-adjusting modelers were evaluated with the results compared. In the second test, 1000 sets of randomly selected six points were selected for prediction with the remaining points used to train the one of the four modelers used. The results are compared to those obtained using the Goodman or Gerber parametric

¹This procedure was suggested by T. Nicholas.

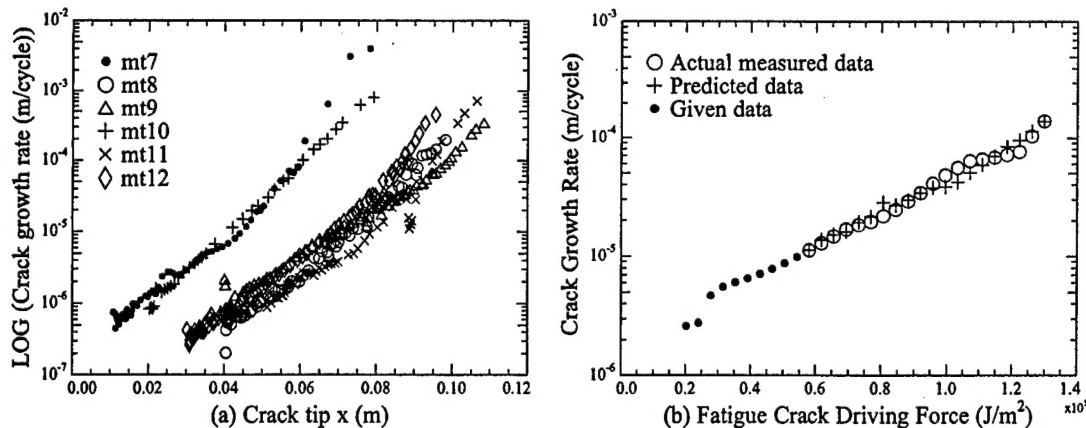


Figure 3: (a) Crack growth rate as a function of crack length for six test specimens subject to different loading configurations; (b) Results of mechanistically-based prediction of a new data set using a *Nadaraya-Watson estimator*.

relations.

In contrast to both the empirical modelers, the self-adjusting modeler is universally applicable. Three evaluation parameters - average relative error, mean relative value and its standard deviation - show that the modelers perform better than either of the parametric relations. Based on the 1000 random data groupings, four evaluation errors are minimized when a modeler was used.

b. Prediction of Crack Growth Rate of Mixed-mode, Fatigue-loaded Specimens

The specific mixed-mode fatigue problem that was studied under this contract was that of a thin aluminum plate loaded under in-plane symmetric tension and out-of-plane antisymmetric torsion. This loading was motivated by the problem of a crack developing in a pressurized aircraft fuselage near a lap splice joint as a result of pressurization and depressurization cycles. We carried out mixed-mode fatigue studies of SEN specimens of 2024-T3 and 7075-T6 Al-alloys.

In applying a modeler to predict the crack growth rate, two kinds of input data were used: One was non-mechanistically based and the other, mechanistically based. In the former, crack growth rate data determined at different *crack lengths* was used to characterize the fatigue process [7]. In the mechanistic approach, one relies on crack growth rate data determined at different *fatigue crack driving forces*. The crack driving force contains information not only about the crack length but also about the applied loads as well as the material properties of the specimen. As Fig. 3(b) demonstrates, by using the *fatigue crack driving force* as one of the descriptors for a cracked specimen, crack growth rates measured under different test conditions can be correlated, resulting in a more robust prediction. Clearly, proper application of the self-adjusting modeler, requires that appropriate information be input to the modeler in order to obtain an accurate prediction.

The work completed under this contract has demonstrated that self-adjusting modelers which are empirical approaches can be used to extract and estimate the physical information em-

bedded in fracture data even though the modelers themselves do not embed any physical basis of the observed phenomena. That is, the modelers can empirically extract the crack growth behavior from measured input data, even though they cannot explain the crack growth law. The modelers are limited by the input data and so they must contain the physical information appropriate to characterize the phenomenon. For crack growth prediction, the input data needs to include information which can be used to identify the damage mechanism, such as, for example, corrosion. Other key variables may include the cyclic test frequency, the loading sequence and history and other parameters which contribute to crack initiation and propagation. Only when all of damage mechanisms and the key variables are recognized and functionally represented in the input data, then can modelers be reliably used in real engineering practice. This work appears in the Ph.D. dissertation of X. Lu and portions of it have been published.

3. *We promised to investigate the use of Lamb plate waves as the basis of a wide-area ultrasonic inspection procedure.*

We considered ultrasonic techniques which are capable of making measurements "at a distance". Promising acoustic sensory systems include those based on active (ultrasonic testing, UT) as well as passive (acoustic emission, AE) ultrasonics which rely on guided wave modes propagating in the structural component. Such waves can easily propagate over long distances in the structure and they contain information about the source or the scatterer, though it is often not easily extracted in the complex guided wave-mode signals which are detected.

A major emphasis of our work was the development of approaches relying on time-frequency analysis of the highly dispersive and complex waveforms which are measured at a far distance (distance \gg plate thickness) from a source in a plate. The signals are such that from ten to twenty Rayleigh-Lamb wave modes are included in the signals. The source may be an active source of acoustic emission such as a crack or possibly a scatterer such as a crack tip in the structure. We developed methods for extracting more information than previously possible from ultrasonic signals propagating in thin plates as used in airframes.

One approach we pursued involved the use of smoothed, pseudo-Wigner-Ville distributions to overlay the measured waveform data. The results exhibit the expected sharp ridges in the time-frequency plane, lying along the predicted frequency-time-of-arrival relations. We have demonstrated that the source-receiver separation can be determined from such plots obtained from just one waveform. This work was presented at the international conference *UI'99/WCU99* in Lyngby, Denmark, July 1999 and published in [8].

The second approach which was begun under this contract and completed only recently is an automatic method for identifying the arrival times of two different wave modes present in a single waveform. These two arrival times are sufficient for determining both the distance to the source and the instant of acoustic source excitation. The method relies on *time-frequency analysis* using the MUSIC spectrum and the root-MUSIC algorithm for harmonic signal identification. [9] With these algorithms, the arrival times of particular plate wave modes can be precisely identified with no human intervention. Our method has the potential to improve failure source location systems.

4. *We promised to investigate the use of acoustic emission source location procedures which will be useful in a hybrid technique for locating and subsequently characterizing regions of damage in plate-like structures.*

We developed a system for locating sources of acoustic emission in a thick, flat plate. The system relies on a small array of sensors to detect the signals, a processing system based on the *automatic modeler* and the development of the memory in this modeler using synthetic waveform data to which are appended encoded source location parameters. The use of a small array of sensors minimizes differences in the effects of wave dispersion and attenuation on the detected signals. No preprocessing of the input waveform data is required. Novel also is that the development of the memory of the modeler is achieved using synthetic waveform data. After training, the modeler can be used to locate actual (simulated) sources of emission. This result was published in Ref. [10].

5. *We agreed to develop a quantitative ultrasonic crack sizing procedure which is self-calibrating and we sought to make the procedure operate autonomously.*

We pioneered a new ultrasonic measurement procedure for determining the location of a crack tip in a plate. The procedure utilizes a multi-element, small transducer array in which the signal detected at least by one of the sensors comprising the array is a crack-tip, diffracted signal. By applying the wavespeed self-consistency condition, the location of the crack tip is determined. This result was published in Ref. [11]

6. *We sought to explore the use of non-linear elasto-dynamic phenomena as the basis of a new non-destructive, wide-area crack detection and sizing procedure.*

Traditional non-linear measurement techniques which have been proposed to detect cracks in materials rely on narrowband ultrasonic bursts to provide a high degree of isolation between the fundamental frequency and its harmonics. But such signals possess poor spatial resolution which makes them unsuitable for locating and sizing cracks. To perform time-resolved, non-linear measurements while still utilizing narrowband bursts which provide a high degree of isolation between the fundamental frequency and any flaw-generated harmonics, we developed a hybrid broadband/narrowband technique that is based on a swept burst and a superheterodyne crosscorrelator to combine the time-resolution of a broadband system with the harmonic isolation of a narrowband burst. We expect that such a measurement capability can be applied to problems, such as the identification and location of non-linear reflectors, for which narrowband non-time-resolved non-linear measurements would be unsuitable.

The first report was presented at the *AFOSR 2000 Metallic Materials Contractors' Meeting*, St. Louis, MO, October 11, 2000 and further results are in [12] and [13].

The work completed under this contract has addressed a wide variety of ultrasonic inspection problems as well as developed a procedure for forecasting the growth rate of a fatigue crack and predicting the lifetime of a specimen that is based on previous measured data. As such, this work lays the foundation for solving a number of practical and challenging problems of interest to the Air Force.

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1. X. Lu, W. Sachse and I. Grabec, "Use of an automatic modeler and a small receiver array for acoustic emission (AE) source location", *Ultrasonics*, **36**, 539-547 (1998).
2. X. Lu, E. Govekar, W. Sachse and I. Grabec, "Synergistic diagnostics of aircraft materials and structures", in *Proceedings of Intelligent NDE Sciences for Aging and Futuristic Aircraft*, C. Ferregut, R. Osegueda and A. Nuñez, eds., Texas Western Press, El Paso, TX (1998), pp. 11-22.
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